

ON THE FRACTIONAL LANE-EMDEN EQUATION

JUAN DÁVILA, LOUIS DUPAIGNE, AND JUNCHENG WEI

ABSTRACT. We classify solutions of finite Morse index of the fractional Lane-Emden equation

$$(-\Delta)^s u = |u|^{p-1} u \quad \text{in } \mathbb{R}^n.$$

1. INTRODUCTION

Fix an integer $n \geq 1$ and let $p_S(n)$ denote the classical Sobolev exponent:

$$p_S(n) = \begin{cases} +\infty & \text{if } n \leq 2 \\ \frac{n+2}{n-2} & \text{if } n \geq 3 \end{cases}$$

A celebrated result of Gidas and Spruck [20] asserts that there is no positive solution to the Lane-Emden equation

$$(1.1) \quad -\Delta u = |u|^{p-1} u \quad \text{in } \mathbb{R}^n,$$

whenever $p \in (1, p_S(n))$. For $p = p_S(n)$, the same equation is known to have (up to translation and rescaling) a unique positive solution, which is radial and explicit (see Caffarelli-Gidas-Spruck [4]). Let now $p_c(n) > p_S(n)$ denote the Joseph-Lundgren exponent:

$$p_c(n) = \begin{cases} +\infty & \text{if } n \leq 10 \\ \frac{(n-2)^2 - 4n + 8\sqrt{n-1}}{(n-2)(n-10)} & \text{if } n \geq 11 \end{cases}$$

This exponent can be characterized as follows: for $p \geq p_S(n)$, the explicit singular solution $u_s(x) = A|x|^{-\frac{2}{p-1}}$ is unstable if and only if $p < p_c(n)$. It was proved by Farina [18] that (1.1) has no nontrivial finite Morse index solution whenever $1 < p < p_c(n)$, $p \neq p_S(n)$.

Through blow-up analysis, such Liouville-type theorems imply interior regularity for solutions of a large class of semilinear elliptic equations: they are known to be equivalent to universal estimates for solutions of

$$(1.2) \quad -Lu = f(x, u, \nabla u) \quad \text{in } \Omega,$$

where L is a uniformly elliptic operator with smooth coefficients, the nonlinearity f scales like $|u|^{p-1}u$ for large values of u , and Ω is an open set of \mathbb{R}^n . For precise statements, see the work of Polacik, Quittner and Souplet [26] in the subcritical setting, as well as its adaptation to the supercritical case by Farina and two of the authors [11].

In the present work, we are interested in understanding whether similar results hold for equations involving a nonlocal diffusion operator, the simplest of which

is perhaps the fractional laplacian. Given $s \in (0, 1)$, the fractional version of the Lane-Emden equation¹ reads

$$(1.3) \quad (-\Delta)^s u = |u|^{p-1} u \quad \text{in } \mathbb{R}^n.$$

Here we have assumed that $u \in C^{2\sigma}(\mathbb{R}^n)$, $\sigma > s$ and

$$(1.4) \quad \int_{\mathbb{R}^n} \frac{|u(y)|}{(1 + |y|)^{n+2s}} dy < +\infty,$$

so that the fractional laplacian of u

$$(-\Delta)^s u(x) := \mathcal{A}_{n,s} \int_{\mathbb{R}^n} \frac{u(x) - u(y)}{|x - y|^{n+2s}} dy$$

is well-defined (in the principal-value sense) at every point $x \in \mathbb{R}^n$. The normalizing constant $\mathcal{A}_{n,s} = \frac{2^{2s-1}}{\pi^{n/2}} \frac{\Gamma(\frac{n+2s}{2})}{|\Gamma(-s)|}$ is of the order of $s(1-s)$ as s converges to 0 or 1.

The aforementioned classification results of Gidas-Spruck and Caffarelli-Gidas-Spruck have been generalized to the fractional setting (see Y. Li [24] and Chen-Li-Ou [8]). The corresponding fractional Sobolev exponent is given by

$$p_S(n) = \begin{cases} +\infty & \text{if } n \leq 2s \\ \frac{n+2s}{n-2s} & \text{if } n > 2s \end{cases}$$

Our main result is the following Liouville-type theorem for the fractional Lane-Emden equation.

Theorem 1.1. *Assume that $n \geq 1$ and $0 < s < \sigma < 1$. Let $u \in C^{2\sigma}(\mathbb{R}^n) \cap L^1(\mathbb{R}^n, (1 + |y|)^{n+2s} dy)$ be a solution to (1.3) which is stable outside a compact set i.e. there exists $R_0 \geq 0$ such that for every $\varphi \in C_c^1(\mathbb{R}^n \setminus \overline{B_{R_0}})$,*

$$(1.5) \quad p \int_{\mathbb{R}^n} |u|^{p-1} \varphi^2 dx \leq \|\varphi\|_{H^s(\mathbb{R}^n)}^2.$$

- If $1 < p < p_S(n)$ or if $p_S(n) < p$ and

$$(1.6) \quad p \frac{\Gamma(\frac{n}{2} - \frac{s}{p-1}) \Gamma(s + \frac{s}{p-1})}{\Gamma(\frac{s}{p-1}) \Gamma(\frac{n-2s}{2} - \frac{s}{p-1})} > \frac{\Gamma(\frac{n+2s}{4})^2}{\Gamma(\frac{n-2s}{4})^2},$$

then $u \equiv 0$;

- If $p = p_S(n)$, then u has finite energy i.e.

$$\|u\|_{H^s(\mathbb{R}^n)}^2 = \int_{\mathbb{R}^n} |u|^{p+1} < +\infty.$$

If in addition u is stable, then in fact $u \equiv 0$.

Remark 1. For $p > p_S(n)$, the function

$$(1.7) \quad u_s(x) = A|x|^{-\frac{2s}{p-1}}$$

where

$$A^{p-1} = \lambda \left(\frac{n-2s}{2} - \frac{2s}{p-1} \right)$$

¹Unlike local diffusion operators, local elliptic regularity for equations of the form (1.2) where this time L is the generator of a general Markov diffusion, cannot be captured from the sole understanding of the fractional Lane-Emden equation. For example, further investigations will be needed for operators of Lévy symbol $\psi(\xi) = \int_{S^{n-1}} |\omega \cdot \xi|^{2s} \mu(d\omega)$, where μ is any finite symmetric measure on the sphere S^{n-1} .

and where

$$(1.8) \quad \lambda(\alpha) = 2^{2s} \frac{\Gamma(\frac{n+2s+2\alpha}{4})\Gamma(\frac{n+2s-2\alpha}{4})}{\Gamma(\frac{n-2s-2\alpha}{4})\Gamma(\frac{n-2s+2\alpha}{4})}$$

is a singular solution to (1.3) (see the work by Montenegro and two of the authors [12] for the case $s = 1/2$, and the work by Fall [16, Lemma 3.1] for the general case). In virtue of the following Hardy inequality (due to Herbst [22])

$$\Lambda_{n,s} \int_{\mathbb{R}^n} \frac{\phi^2}{|x|^{2s}} dx \leq \|\phi\|_{\dot{H}^s(\mathbb{R}^n)}^2$$

with optimal constant given by

$$\Lambda_{n,s} = 2^{2s} \frac{\Gamma(\frac{n+2s}{4})^2}{\Gamma(\frac{n-2s}{4})^2},$$

u_s is unstable if only if (1.6) holds. Let us also mention that regular radial solutions in the case $s = 1/2$ were constructed by Chipot, Chlebik ad Shafrir [9]. Recently, Harada [21] proved that for $s = 1/2$, condition (1.6) is the dividing line for the asymptotic behavior of radial solutions to (1.3), extending thereby the classical results of Joseph and Lundgren [23] to the fractional Lane-Emden equation in the case $s = 1/2$. A similar technique as in [9] allows us to show that the condition (1.6) is optimal. Indeed we have:

Theorem 1.2. *Assume $p > p_S(n)$ and that (1.6) fails. Then there are radial smooth solutions $u > 0$ with $u(r) \rightarrow 0$ as $r \rightarrow \infty$ of (1.3) that are stable.*

It is by now standard knowledge that the fractional laplacian can be seen as a Dirichlet-to-Neumann operator for a degenerate but *local* diffusion operator in the higher-dimensional half-space \mathbb{R}_+^{n+1} :

Theorem 1.3 ([5, 25, 28]). *Take $s \in (0, 1)$, $\sigma > s$ and $u \in C^{2\sigma}(\mathbb{R}^n) \cap L^1(\mathbb{R}^n, (1 + |y|)^{n+2s} dy)$. For $X = (x, t) \in \mathbb{R}_+^{n+1}$, let*

$$\bar{u}(X) = \int_{\mathbb{R}^n} P(X, y) u(y) dy,$$

where

$$P(X, y) = p_{n,s} t^{2s} |X - y|^{-(n+2s)}$$

and $p_{n,s}$ is chosen so that $\int_{\mathbb{R}^n} P(X, y) dy = 1$. Then, $\bar{u} \in C^2(\mathbb{R}_+^{n+1}) \cap C(\overline{\mathbb{R}_+^{n+1}})$, $t^{1-2s} \partial_t \bar{u} \in C(\overline{\mathbb{R}_+^{n+1}})$ and

$$\begin{cases} \nabla \cdot (t^{1-2s} \nabla \bar{u}) = 0 & \text{in } \mathbb{R}_+^{n+1}, \\ \bar{u} = u & \text{on } \partial \mathbb{R}_+^{n+1}, \\ -\lim_{t \rightarrow 0} t^{1-2s} \partial_t \bar{u} = \kappa_s (-\Delta)^s u & \text{on } \partial \mathbb{R}_+^{n+1}, \end{cases}$$

where

$$(1.9) \quad \kappa_s = \frac{\Gamma(1-s)}{2^{2s-1} \Gamma(s)}.$$

Applying Theorem 1.3 to a solution of the fractional Lane-Emden equation, we end up with the equation

$$(1.10) \quad \begin{cases} -\nabla \cdot (t^{1-2s} \nabla \bar{u}) = 0 & \text{in } \mathbb{R}_+^{n+1} \\ -\lim_{t \rightarrow 0} t^{1-2s} \partial_t \bar{u} = \kappa_s |\bar{u}|^{p-1} \bar{u} & \text{on } \partial \mathbb{R}_+^{n+1} \end{cases}$$

An essential ingredient in the proof of Theorem 1.1 is the following monotonicity formula

Theorem 1.4. *Take a solution to (1.10) $\bar{u} \in C^2(\mathbb{R}_+^{n+1}) \cap C(\overline{\mathbb{R}_+^{n+1}})$ such that $t^{1-2s} \partial_t \bar{u} \in C(\overline{\mathbb{R}_+^{n+1}})$. For $x_0 \in \partial \mathbb{R}_+^{n+1}$, $\lambda > 0$, let*

$$\begin{aligned} E(\bar{u}, x_0; \lambda) = & \lambda^{2s \frac{p+1}{p-1} - n} \left(\frac{1}{2} \int_{\mathbb{R}_+^{n+1} \cap B(x_0, \lambda)} t^{1-2s} |\nabla \bar{u}|^2 dx dt - \frac{\kappa_s}{p+1} \int_{\partial \mathbb{R}_+^{n+1} \cap B(x_0, \lambda)} |\bar{u}|^{p+1} dx \right) \\ & + \lambda^{2s \frac{p+1}{p-1} - n-1} \frac{s}{p+1} \int_{\partial B(x_0, \lambda) \cap \mathbb{R}_+^{n+1}} t^{1-2s} \bar{u}^2 d\sigma. \end{aligned}$$

Then, E is a nondecreasing function of λ . Furthermore,

$$\frac{dE}{d\lambda} = \lambda^{2s \frac{p+1}{p-1} - n+1} \int_{\partial B(x_0, \lambda) \cap \mathbb{R}_+^{n+1}} t^{1-2s} \left(\frac{\partial \bar{u}}{\partial r} + \frac{2s}{p-1} \frac{\bar{u}}{r} \right)^2 d\sigma$$

Remark 2. In the above, $B(x_0, \lambda)$ denotes the euclidean ball in \mathbb{R}_+^{n+1} centered at x_0 of radius λ , σ the n -dimensional Hausdorff measure restricted to $\partial B(x_0, \lambda)$, $r = |X|$ the euclidean norm of a point $X = (x, t) \in \mathbb{R}_+^{n+1}$, and $\partial_r = \nabla \cdot \frac{X}{r}$ the corresponding radial derivative.

An analogous monotonicity formula has been derived by Fall and Felli [17] to obtain unique continuation results for fractional equations. Previously, Caffarelli and Silvestre derived an Almgren quotient formula for the fractional laplacian in [5] and Caffarelli, Roquejoffre and Savin [6] obtained a related monotonicity formula to study regularity of nonlocal minimal surfaces. Another monotonicity formula for fractional problems was obtained by Cabré and Sire [3] and used by Frank, Lenzmann and Silvestre [19].

The proof of Theorem 1.1 follows an approach used in our earlier work with Kelei Wang [13] (see also [29]). First we derive suitable energy estimate (Section 2) and handle the critical and subcritical cases (Section 3). In Section 4 we give a proof of the monotonicity formula Theorem 1.4. Then we use the monotonicity formula and a blown-down analysis (Section 6) to reduce to homogeneous singular solutions. We exclude the existence of stable homogeneous singular solutions in the optimal range of p (Section 5). Finally we prove Theorem 1.2 in Section 7.

2. ENERGY ESTIMATES

Lemma 2.1. *Let u be a solution to (1.3). Assume that u is stable outside some ball $B_{R_0} \subset \mathbb{R}^n$. Let $\eta \in C_c^\infty(\mathbb{R}^n \setminus \overline{B_{R_0}})$ and for $x \in \mathbb{R}^n$, define*

$$(2.1) \quad \rho(x) = \int_{\mathbb{R}^n} \frac{(\eta(x) - \eta(y))^2}{|x - y|^{n+2s}} dy$$

Then,

$$\int_{\mathbb{R}^n} |u|^{p+1} \eta^2 dx + \frac{1}{p} \|u\eta\|_{\dot{H}^s(\mathbb{R}^n)}^2 \leq \frac{2}{p-1} \int_{\mathbb{R}^n} u^2 \rho dx.$$

Proof. Multiply (1.3) by $u\eta^2$. Then,

$$\begin{aligned} \int_{\mathbb{R}^n} |u|^{p+1} \eta^2 dx &= \int_{\mathbb{R}^n} (-\Delta)^s u u \eta^2 dx \\ &= \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{(u(x) - u(y))(u(x)\eta(x)^2 - u(y)\eta(y)^2)}{|x - y|^{n+2s}} dx dy \\ &= \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{u^2(x)\eta^2(x) - u(x)u(y)(\eta^2(x) + \eta^2(y)) + u^2(y)\eta^2(y)}{|x - y|^{n+2s}} dx dy \\ &= \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{(u(x)\eta(x) - u(y)\eta(y))^2 - (\eta(x) - \eta(y))^2 u(x)u(y)}{|x - y|^{n+2s}} dx dy \\ &= \|u\eta\|_{\dot{H}^s(\mathbb{R}^n)}^2 - \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{(\eta(x) - \eta(y))^2 u(x)u(y)}{|x - y|^{n+2s}} dx dy \end{aligned}$$

Using the inequality $2ab \leq a^2 + b^2$, we deduce that

$$(2.2) \quad \|u\eta\|_{\dot{H}^s(\mathbb{R}^n)}^2 - \int_{\mathbb{R}^n} |u|^{p+1} \eta^2 dx \leq \int_{\mathbb{R}^n} u^2 \rho dx$$

Since u is stable, we deduce that

$$(p-1) \int_{\mathbb{R}^n} |u|^{p+1} \eta^2 dx \leq \int_{\mathbb{R}^n} u^2 \rho dx$$

Going back to (2.2), it follows that

$$\frac{1}{p} \|u\eta\|_{\dot{H}^s(\mathbb{R}^n)}^2 + \int_{\mathbb{R}^n} |u|^{p+1} \eta^2 dx \leq \frac{2}{p-1} \int_{\mathbb{R}^n} u^2 \rho dx$$

□

Lemma 2.2. For $m > n/2$ and $x \in \mathbb{R}^n$, let

$$(2.3) \quad \eta(x) = (1 + |x|^2)^{-m/2} \quad \text{and} \quad \rho(x) = \int_{\mathbb{R}^n} \frac{(\eta(x) - \eta(y))^2}{|x - y|^{n+2s}} dy$$

Then, there exists a constant $C = C(n, s, m) > 0$ such that

$$(2.4) \quad C^{-1} (1 + |x|^2)^{-\frac{n}{2}-s} \leq \rho(x) \leq C (1 + |x|^2)^{-\frac{n}{2}-s}.$$

Proof. Let us prove the upper bound first. Since ρ is a continuous function, we may always assume that $|x| \geq 1$. Split the integral

$$\int_{\mathbb{R}^n} \frac{(\eta(x) - \eta(y))^2}{|x - y|^{n+2s}} dy$$

in the regions $|x - y| < |x|/2$, $|x|/2 \leq |x - y| \leq 2|x|$, and $|x - y| > 2|x|$. When $|x - y| \leq |x|/2$,

$$|\eta(x) - \eta(y)| \leq C(1 + |x|^2)^{-\frac{m+1}{2}} |x - y|.$$

So,

$$\begin{aligned} \int_{|x-y| \leq |x|/2} \frac{(\eta(x) - \eta(y))^2}{|x - y|^{n+2s}} dy &\leq C(1 + |x|^2)^{-m-1} \int_{|x-y| \leq |x|/2} |x - y|^{2-n-2s} dy \\ &\leq C(1 + |x|^2)^{-m-s} \leq C(1 + |x|^2)^{-\frac{n}{2}-s}. \end{aligned}$$

When $|x|/2 \leq |x-y| \leq 2|x|$,

$$\begin{aligned} \int_{|x|/2 \leq |x-y| \leq 2|x|} \frac{(\eta(x) - \eta(y))^2}{|x-y|^{n+2s}} dy &\leq C|x|^{-n-2s} \int_{|y| \leq 2|x|} (\eta(x)^2 + \eta(y)^2) dy \\ &\leq C|x|^{-n-2s} (|x|^{-2m+n} + 1) \leq C(1 + |x|^2)^{-\frac{n}{2}-s}, \end{aligned}$$

where we used the assumption $m > \frac{n}{2}$. When $|x-y| > 2|x|$, then $|y| \geq |x|$ and $\eta(y) \leq C(1 + |x|^2)^{-m/2}$. Then,

$$\begin{aligned} \int_{|x-y| > 2|x|} \frac{(\eta(x) - \eta(y))^2}{|x-y|^{n+2s}} dy &\leq C(1 + |x|^2)^{-m} \int_{|x-y| > 2|x|} \frac{1}{|x-y|^{n+2s}} dy \\ &\leq C(1 + |x|^2)^{-m-s} \leq C(1 + |x|^2)^{-\frac{n}{2}-s}. \end{aligned}$$

Let us turn to the lower bound. Again, we may always assume that $|x| \geq 1$. Then,

$$\rho(x) \geq \int_{|y| \leq 1/2} \frac{(\eta(y) - \eta(x))^2}{|x-y|^{n+2s}} dy \geq \left(\frac{|x|}{2}\right)^{-(n+2s)} \int_{|y| \leq 1/2} (\eta(y) - 2^{-m/2})^2 dy$$

and the estimate follows. \square

Corollary 2.3. *Let $m > n/2$, η given by (2.3), $R \geq R_0 \geq 1$, $\psi \in C^\infty(\mathbb{R}^n)$ be such that $0 \leq \psi \leq 1$, $\psi \equiv 0$ on B_1 and $\psi \equiv 1$ on $\mathbb{R}^n \setminus B_2$. Let*

$$(2.5) \quad \eta_R(x) = \eta\left(\frac{x}{R}\right) \psi\left(\frac{x}{R_0}\right) \quad \text{and} \quad \rho_R(x) = \int_{\mathbb{R}^n} \frac{(\eta_R(x) - \eta_R(y))^2}{|x-y|^{n+2s}} dy$$

There exists a constant $C = C(n, s, m, R_0) > 0$ such that for all $|x| \geq 3R_0$

$$\rho_R(x) \leq C\eta\left(\frac{x}{R}\right)^2 |x|^{-(n+2s)} + R^{-2s} \rho\left(\frac{x}{R}\right)$$

Proof. Fix x such that $|x| \geq R \geq 3R_0$. Using the definition of η_R and Young's inequality, we have

$$\begin{aligned} \frac{1}{2}\rho_R(x) &\leq \eta\left(\frac{x}{R}\right)^2 \int_{\mathbb{R}^n} \frac{\left(\psi\left(\frac{x}{R_0}\right) - \psi\left(\frac{y}{R_0}\right)\right)^2}{|x-y|^{n+2s}} dy + \int_{\mathbb{R}^n} \psi\left(\frac{y}{R_0}\right)^2 \frac{(\eta\left(\frac{x}{R}\right) - \eta\left(\frac{y}{R}\right))^2}{|x-y|^{n+2s}} dy \\ &\leq \eta\left(\frac{x}{R}\right)^2 \int_{B_{2R_0}} \frac{1}{|x-y|^{n+2s}} dy + \int_{\mathbb{R}^n} \frac{(\eta\left(\frac{x}{R}\right) - \eta\left(\frac{y}{R}\right))^2}{|x-y|^{n+2s}} dy \\ &\leq C\eta\left(\frac{x}{R}\right)^2 |x|^{-(n+2s)} + R^{-2s} \rho\left(\frac{x}{R}\right) \end{aligned}$$

and the result follows. \square

Lemma 2.4. *Let u be a solution of (1.3) which is stable outside a ball B_{R_0} . Take ρ_R as in Corollary 2.3 with $m \in (\frac{n}{2}, \frac{n}{2} + \frac{s(p+1)}{2})$. Then, there exists a constant $C = C(n, s, m, p, R_0) > 0$ such that for all $R \geq 3R_0$,*

$$\int_{\mathbb{R}^n} u^2 \rho_R dx \leq C \left(\int_{B_{3R_0}} u^2 \rho_R dx + R^{n-2s} \frac{p+1}{p-1} \right).$$

Proof. By Corollary 2.3, if $R \geq |x| \geq 3R_0$, then

$$\rho_R(x) \leq C(|x|^{-n-2s} + R^{-2s})$$

and so

$$\int_{B_R \setminus B_{3R_0}} \rho_R(x)^{\frac{p+1}{p-1}} \eta_R(x)^{-\frac{4}{p-1}} dx \leq C R^{n-2s} \frac{p+1}{p-1}.$$

Similarly, if $|x| \geq R \geq 3R_0$, then

$$\rho_R(x) \leq C R^{-2s} \left(1 + \frac{|x|^2}{R^2}\right)^{-\frac{n}{2}-s}$$

and so

$$\rho_R(x)^{\frac{p+1}{p-1}} \eta_R(x)^{-\frac{4}{p-1}} \leq C R^{-2s} \frac{p+1}{p-1} \left(1 + \frac{|x|^2}{R^2}\right)^{-\frac{n+2s}{2} \frac{p+1}{p-1} + \frac{2m}{p-1}}$$

Since $m \in (\frac{n}{2}, \frac{n}{2} + s \frac{p+1}{2})$, we have $\frac{2m}{p-1} - \frac{n+2s}{2} \frac{p+1}{p-1} < -\frac{n}{2}$ and so

$$\int_{\mathbb{R}^n \setminus B_{3R_0}} \rho_R(x)^{\frac{p+1}{p-1}} \eta_R(x)^{-\frac{4}{p-1}} dx \leq C R^{n-2s} \frac{p+1}{p-1}.$$

Now,

$$\begin{aligned} \int_{\mathbb{R}^n} u^2 \rho_R dx &= \int_{B_{3R_0}} u^2 \rho_R dx + \int_{\mathbb{R}^n \setminus B_{3R_0}} u^2 \rho_R \eta_R^{-\frac{4}{p+1}} \eta_R^{\frac{4}{p+1}} dx \\ &\leq \int_{B_{3R_0}} u^2 \rho_R dx + \left(\int_{\mathbb{R}^n} |u|^{p+1} \eta_R^2 dx \right)^{\frac{2}{p+1}} \left(\int_{\mathbb{R}^n} \rho_R^{\frac{p+1}{p-1}} \eta_R^{-\frac{4}{p-1}} dx \right)^{\frac{p-1}{p+1}} \\ &\leq \int_{B_{3R_0}} u^2 \rho_R dx + C R^{(n-2s) \frac{p+1}{p-1} \frac{p-1}{p+1}} \left(\int_{\mathbb{R}^n} |u|^{p+1} \eta_R^2 dx \right)^{\frac{2}{p+1}} \end{aligned}$$

By a standard approximation argument, Lemma 2.1 remains valid with $\eta = \eta_R$ and $\rho = \rho_R$ and so the result follows. \square

Lemma 2.5. Assume that $p \neq \frac{n+2s}{n-2s}$. Let u be a solution to (1.3) which is stable outside a ball B_{R_0} and \bar{u} its extension, solving (1.10). Then, there exists a constant $C = C(n, p, s, R_0, u) > 0$ such that

$$\int_{B_R} t^{1-2s} \bar{u}^2 dx dt \leq C R^{n+2(1-s) - \frac{4s}{p-1}}$$

for any $R > 3R_0$.

Proof. According to Theorem 1.3,

$$\bar{u}(x, t) = p_{n,s} \int_{\mathbb{R}^n} u(z) \frac{t^{2s}}{(|x-z|^2 + t^2)^{\frac{n+2s}{2}}} dz$$

so that

$$\bar{u}(x, t)^2 \leq p_{n,s} \int_{\mathbb{R}^n} u(z)^2 \frac{t^{2s}}{(|x-z|^2 + t^2)^{\frac{n+2s}{2}}} dz.$$

So,

$$\begin{aligned} \int_{B_R} t^{1-2s} \bar{u}^2 dx dt &\leq p_{n,s} \int_{|x| \leq R, z \in \mathbb{R}^n} u(z)^2 \left(\int_0^R \frac{t}{(|x-z|^2 + t^2)^{\frac{n+2s}{2}}} dt \right) dz dx \\ &\leq C \int_{|x| \leq R, z \in \mathbb{R}^n} u^2(z) \left\{ (|x-z|^2)^{-\frac{n}{2}+1-s} - (|x-z|^2 + R^2)^{-\frac{n}{2}+1-s} \right\} dz dx \end{aligned}$$

Split this last integral according to $|x - z| < 2R$ or $|x - z| \geq 2R$. Then,

$$\begin{aligned} & \int_{|x| \leq R, |x-z| < 2R} u^2(z) \left\{ (|x-z|^2)^{-\frac{n}{2}+1-s} - (|x-z|^2 + R^2)^{-\frac{n}{2}+1-s} \right\} dz dx \leq \\ & \int_{|x| \leq R, |x-z| < 2R} u^2(z) (|x-z|^2)^{-\frac{n}{2}+1-s} dz dx \leq CR^{2(1-s)} \int_{B_{3R}} u^2(z) dz \leq \\ & CR^{2(1-s)} \left(\int |u|^{p+1} \eta_R^2 \right)^{\frac{2}{p+1}} \left(\int_{B_{3R}} \eta_R^{-\frac{4}{p-1}} \right)^{\frac{p-1}{p+1}} \leq \\ & CR^{2(1-s)+n\frac{p-1}{p+1}} \left(\int u^2(z) \rho_R(z) dz \right)^{\frac{2}{p+1}} \leq CR^{n+2(1-s)-\frac{4s}{p-1}}, \end{aligned}$$

where we used Hölder's inequality, then Lemma 2.1 and then Lemma 2.4. For the region $|x - z| \geq 2R$, the mean-value inequality implies that

$$\begin{aligned} & \int_{|x| \leq R, |x-z| \geq 2R} u^2(z) \left\{ (|x-z|^2)^{-\frac{n}{2}+1-s} - (|x-z|^2 + R^2)^{-\frac{n}{2}+1-s} \right\} dz dx \leq \\ & CR^2 \int_{|x| \leq R, |x-z| \geq 2R} u^2(z) |x-z|^{-(n+2s)} dz dx \leq CR^{n+2} \int_{|z| \geq R} u^2(z) |z|^{-(n+2s)} dz \\ & \leq CR^2 \int_{|z| \geq R} u^2 \rho dz \leq CR^{n+2(1-s)-\frac{4s}{p-1}}, \end{aligned}$$

where we used again Corollary 2.3 in the penultimate inequality and Lemma 2.4 in the last one. \square

Lemma 2.6. *Let u be a solution to (1.3) which is stable outside a ball B_{R_0} and \bar{u} its extension, solving (1.10). Then, there exists a constant $C = C(n, p, s, u) > 0$ such that*

$$\int_{B_R \cap \mathbb{R}_+^{n+1}} t^{1-2s} |\nabla \bar{u}|^2 dx dt + \int_{B_R \cap \partial \mathbb{R}_+^{n+1}} |u|^{p+1} dx \leq CR^{n-2s\frac{p+1}{p-1}}$$

Proof. The L^{p+1} estimate follows from Lemmata 2.1 and 2.4. Now take a cut-off function $\eta \in C_c^1(\overline{\mathbb{R}_+^{n+1}})$ such that $\eta = 1$ on $\mathbb{R}_+^{n+1} \cap (B_R \setminus B_{2R_0})$ and $\eta = 0$ on $B_{R_0} \cup (\mathbb{R}_+^{n+1} \setminus B_{2R})$, and multiply equation (1.10) by $\bar{u}\eta^2$. Then,

$$\begin{aligned} \kappa_s \int_{\partial \mathbb{R}_+^{n+1}} |\bar{u}|^{p+1} \eta^2 dx &= \int_{\mathbb{R}_+^{n+1}} t^{1-2s} \{ \nabla \bar{u} \cdot \nabla (\bar{u}\eta^2) \} dx dt \\ (2.6) \quad &= \int_{\mathbb{R}_+^{n+1}} t^{1-2s} \{ |\nabla(\bar{u}\eta)|^2 - \bar{u}^2 |\nabla \eta|^2 \} dx dt. \end{aligned}$$

Since u is stable outside B_{R_0} , so is \bar{u} and we deduce that

$$\frac{1}{p} \int_{\mathbb{R}_+^{n+1}} t^{1-2s} |\nabla(\bar{u}\eta)|^2 dx dt \geq \int_{\mathbb{R}_+^{n+1}} t^{1-2s} \{ |\nabla(\bar{u}\eta)|^2 - \bar{u}^2 |\nabla \eta|^2 \} dx dt.$$

In other words,

$$(2.7) \quad p' \int_{\mathbb{R}_+^{n+1}} t^{1-2s} \bar{u}^2 |\nabla \eta|^2 dx dt \geq \int_{\mathbb{R}_+^{n+1}} t^{1-2s} |\nabla(\bar{u}\eta)|^2 dx dt,$$

where $\frac{1}{p'} + \frac{1}{p} = 1$. We then apply Lemma 2.5. \square

3. THE SUBCRITICAL CASE

In this section, we prove Theorem 1.1 for $1 < p \leq p_S(n)$.

Proof. Take a solution u which is stable outside some ball B_{R_0} . Apply Lemma 2.4 and let $R \rightarrow +\infty$. Since $p \leq p_S(n)$, we deduce that $u \in \dot{H}^s(\mathbb{R}^n) \cap L^{p+1}(\mathbb{R}^n)$. Multiplying the equation (1.3) by u and integrating, we deduce that

$$(3.1) \quad \int_{\mathbb{R}^n} |u|^{p+1} = \|u\|_{\dot{H}^s(\mathbb{R}^n)}^2,$$

while multiplying by u^λ given for $\lambda > 0$ and $x \in \mathbb{R}^n$ by

$$u^\lambda(x) = u(\lambda x)$$

yields

$$\int_{\mathbb{R}^n} |u|^{p-1} u^\lambda = \int_{\mathbb{R}^n} (-\Delta)^{s/2} u (-\Delta)^{s/2} u^\lambda = \lambda^s \int_{\mathbb{R}^n} w w^\lambda,$$

where $w = (-\Delta)^{s/2} u$. Following Ros-Oton and Serra [27], we use the change of variable $y = \sqrt{\lambda} x$ to deduce that

$$\lambda^s \int_{\mathbb{R}^n} w w^\lambda dx = \lambda^{\frac{2s-n}{2}} \int_{\mathbb{R}^n} w^{\sqrt{\lambda}} w^{1/\sqrt{\lambda}} dy$$

Hence,

$$\begin{aligned} -\frac{n}{p+1} \int_{\mathbb{R}^n} |u|^{p+1} &= \int_{\mathbb{R}^n} x \cdot \nabla \frac{|u|^{p+1}}{p+1} = \int_{\mathbb{R}^n} (|u|^{p-1} u) x \cdot \nabla u = \\ &= \frac{d}{d\lambda} \Big|_{\lambda=1} \int_{\mathbb{R}^n} |u|^{p-1} u u^\lambda = \frac{d}{d\lambda} \Big|_{\lambda=1} \lambda^{\frac{2s-n}{2}} \int_{\mathbb{R}^n} w^{\sqrt{\lambda}} w^{1/\sqrt{\lambda}} dy = \\ &= \frac{2s-n}{2} \int_{\mathbb{R}^n} w^2 + \frac{d}{d\lambda} \Big|_{\lambda=1} \int_{\mathbb{R}^n} w^{\sqrt{\lambda}} w^{1/\sqrt{\lambda}} dy = \frac{2s-n}{2} \|u\|_{\dot{H}^s(\mathbb{R}^n)}^2 \end{aligned}$$

In the last equality, we have used the fact that $w \in C^1(\mathbb{R}^n)$, as follows by elliptic regularity. We have just proved the following Pohozaev identity

$$\frac{n}{p+1} \int_{\mathbb{R}^n} |u|^{p+1} = \frac{n-2s}{2} \|u\|_{\dot{H}^s(\mathbb{R}^n)}^2$$

For $p < p_S(n)$, the above identity together with (3.1) force $u \equiv 0$. For $p = p_S(n)$, we are left with proving that there is no stable nontrivial solution. Since $u \in \dot{H}^s(\mathbb{R}^n)$, we may apply the stability inequality (1.5) with test function $\varphi = u$, so that

$$p \int_{\mathbb{R}^n} |u|^{p+1} \leq \|u\|_{\dot{H}^s(\mathbb{R}^n)}^2.$$

This contradicts (3.1) unless $u \equiv 0$. \square

In the following sections, we present several tools to study the supercritical case.

4. THE MONOTONICITY FORMULA

In this section, we prove Theorem 1.4.

Proof. Since the equation is invariant under translation, it suffices to consider the case where the center of the considered ball is the origin $x_0 = 0$. Let

$$(4.1) \quad E_1(\bar{u}; \lambda) = \lambda^{2s \frac{p+1}{p-1} - n} \left(\int_{\mathbb{R}_+^{n+1} \cap B_\lambda} t^{1-2s} \frac{|\nabla \bar{u}|^2}{2} dx dt - \int_{\partial \mathbb{R}_+^{n+1} \cap B_\lambda} \frac{\kappa_s}{p+1} |\bar{u}|^{p+1} dx \right)$$

For $X \in \mathbb{R}_+^{n+1}$, let also

$$(4.2) \quad U(X; \lambda) = \lambda^{\frac{2s}{p-1}} \bar{u}(\lambda X).$$

Then, U satisfies the three following properties: U solves (1.10),

$$(4.3) \quad E_1(\bar{u}; \lambda) = E_1(U; 1),$$

and, using subscripts to denote partial derivatives,

$$(4.4) \quad \lambda U_\lambda = \frac{2s}{p-1} U + r U_r.$$

Differentiating the right-hand side of (4.3), we find

$$\frac{dE_1}{d\lambda}(\bar{u}; \lambda) = \int_{\mathbb{R}_+^{n+1} \cap B_1} t^{1-2s} \nabla U \cdot \nabla U_\lambda dx dt - \kappa_s \int_{\partial \mathbb{R}_+^{n+1} \cap B_1} |U|^{p-1} U_\lambda dx.$$

Integrating by parts and then using (4.4),

$$\begin{aligned} \frac{dE_1}{d\lambda}(\bar{u}; \lambda) &= \int_{\partial B_1 \cap \mathbb{R}_+^{n+1}} t^{1-2s} U_r U_\lambda d\sigma \\ &= \lambda \int_{\partial B_1 \cap \mathbb{R}_+^{n+1}} t^{1-2s} U_\lambda^2 d\sigma - \frac{2s}{p-1} \int_{\partial B_1 \cap \mathbb{R}_+^{n+1}} t^{1-2s} U U_\lambda d\sigma \\ &= \lambda \int_{\partial B_1 \cap \mathbb{R}_+^{n+1}} t^{1-2s} U_\lambda^2 d\sigma - \frac{s}{p-1} \left(\int_{\partial B_1 \cap \mathbb{R}_+^{n+1}} t^{1-2s} U^2 d\sigma \right)_\lambda \end{aligned}$$

Scaling back, the theorem follows. \square

5. HOMOGENEOUS SOLUTIONS

Theorem 5.1. *Let \bar{u} be a stable homogeneous solution of (1.10). Assume that $p > \frac{n+2s}{n-2s}$ and*

$$(5.1) \quad p \frac{\Gamma(\frac{n}{2} - \frac{s}{p-1}) \Gamma(s + \frac{s}{p-1})}{\Gamma(\frac{s}{p-1}) \Gamma(\frac{n-2s}{2} - \frac{s}{p-1})} > \frac{\Gamma(\frac{n+2s}{4})^2}{\Gamma(\frac{n-2s}{4})^2}.$$

Then, $\bar{u} \equiv 0$.

Proof. Take standard polar coordinates in \mathbb{R}_+^{n+1} : $X = (x, t) = r\theta$, where $r = |X|$ and $\theta = \frac{X}{|X|}$. Let $\theta_1 = \frac{t}{|X|}$ denote the component of θ in the t direction and $S_+^n = \{X \in \mathbb{R}_+^{n+1} : r = 1, \theta_1 > 0\}$ denote the upper unit half-sphere.

Step 1. Let \bar{u} be a homogeneous solution of (1.10) i.e. assume that for some $\psi \in C^2(S_+^n)$,

$$\bar{u}(X) = r^{-\frac{2s}{p-1}} \psi(\theta).$$

Then,

$$(5.2) \quad \int_{S_+^n} \theta_1^{1-2s} |\nabla \psi|^2 + \beta \int_{S_+^n} \theta_1^{1-2s} \psi^2 = \kappa_s \int_{\partial S_+^n} |\psi|^{p+1},$$

where κ_s is given by (1.9) and

$$\beta = \frac{2s}{p-1} \left(n - 2s - \frac{2s}{p-1} \right).$$

Indeed, since \bar{u} solves (1.10) and is homogeneous, ψ solves

$$(5.3) \quad \begin{cases} -\operatorname{div}(\theta_1^{1-2s} \nabla \psi) + \beta \theta_1^{1-2s} \psi = 0 & \text{on } S_+^n \\ -\lim_{\theta_1 \rightarrow 0} \theta_1^{1-2s} \partial_{\theta_1} \psi = \kappa_s |\psi|^{p-1} \psi & \text{on } \partial S_+^n, \end{cases}$$

Multiplying (5.3) by ψ and integrating, (5.2) follows.

Step 2. For all $\varphi \in C^1(S_+^n)$,

$$(5.4) \quad \kappa_s p \int_{\partial S_+^n} |\psi|^{p-1} \varphi^2 \leq \int_{S_+^n} \theta_1^{1-2s} |\nabla \varphi|^2 + \left(\frac{n-2s}{2} \right)^2 \int_{S_+^n} \theta_1^{1-2s} \varphi^2$$

By definition, \bar{u} is stable if for all $\phi \in C_c^1(\overline{\mathbb{R}_+^{n+1}})$,

$$(5.5) \quad \kappa_s p \int_{\partial \mathbb{R}_+^{n+1}} |\bar{u}|^{p-1} \phi^2 dx \leq \int_{\mathbb{R}_+^{n+1}} t^{1-2s} |\nabla \phi|^2 dx dt$$

Choose a standard cut-off function $\eta_\epsilon \in C_c^1(\mathbb{R}_+^*)$ at the origin and at infinity i.e. $\chi_{(\epsilon, 1/\epsilon)}(r) \leq \eta_\epsilon(r) \leq \chi_{(\epsilon/2, 2/\epsilon)}(r)$. Let also $\varphi \in C^1(S_+^n)$, apply (5.5) with

$$\phi(X) = r^{-\frac{n-2s}{2}} \eta_\epsilon(r) \varphi(\theta) \quad \text{for } X \in \mathbb{R}_+^{n+1},$$

and let $\epsilon \rightarrow 0$. Inequality (5.4) follows.

Step 3. For $\alpha \in (0, \frac{n-2s}{2})$, $x \in \mathbb{R}^n \setminus \{0\}$, let

$$v_\alpha(x) = |x|^{-\frac{n-2s}{2} + \alpha}$$

and \bar{v}_α its extension, as defined in Theorem 1.3. Then, \bar{v}_α is homogeneous i.e. there exists $\phi_\alpha \in C^2(S_+^n)$ such that for $X \in \mathbb{R}_+^{n+1} \setminus \{0\}$,

$$\bar{v}_\alpha(X) = r^{-\frac{n-2s}{2} + \alpha} \phi_\alpha(\theta).$$

In addition, for all $\varphi \in C^1(S_+^n)$,

$$(5.6) \quad \begin{aligned} \int_{S_+^n} \theta_1^{1-2s} |\nabla \varphi|^2 + \left(\left(\frac{n-2s}{2} \right)^2 - \alpha^2 \right) \int_{S_+^n} \theta_1^{1-2s} \varphi^2 \\ = \kappa_s \lambda(\alpha) \int_{\partial S_+^n} \varphi^2 + \int_{S_+^n} \theta_1^{1-2s} \phi_\alpha^2 \left| \nabla \left(\frac{\varphi}{\phi_\alpha} \right) \right|^2 \end{aligned}$$

Indeed, according to Fall [16, Lemma 3.1], \bar{v}_α is homogeneous. Using the calculus identity stated by Fall-Felli in [17, Lemma 2.1], we get

$$(5.7) \quad \begin{cases} -\operatorname{div}(\theta_1^{1-2s} \nabla \phi_\alpha) + \left(\left(\frac{n-2s}{2} \right)^2 - \alpha^2 \right) \theta_1^{1-2s} \phi_\alpha = 0 & \text{on } S_+^n \\ \phi_\alpha = 1 & \text{on } \partial S_+^n. \end{cases}$$

Multiply equation (5.7) by φ^2/ϕ_α , integrate by parts, apply the calculus identity

$$\nabla \phi_\alpha \cdot \nabla \frac{\varphi^2}{\phi_\alpha} = |\nabla \varphi|^2 - \left| \nabla \frac{\varphi}{\phi_\alpha} \right|^2 \phi_\alpha^2$$

and recall from Fall [16, Lemma 3.1] that

$$-\lim_{t \rightarrow 0} t^{1-2s} \partial_t \bar{v}_\alpha = \kappa_s \lambda(\alpha) |x|^{-\frac{n-2s}{2} + \alpha - 2s},$$

where $\lambda(\alpha)$ is given by (1.8).

Step 4. For $\alpha \in (0, \frac{n-2s}{2})$

$$(5.8) \quad \phi_0 \leq \phi_\alpha \quad \text{on } S_+^n.$$

Indeed, on S_+^n ,

$$\operatorname{div}(\theta_1^{1-2s} \nabla \phi_0) = \left(\frac{n-2s}{2} \right)^2 \theta_1^{1-2s} \phi_0 \geq \left(\left(\frac{n-2s}{2} \right)^2 - \alpha^2 \right) \theta_1^{1-2s} \phi_0$$

so ϕ_0 is a sub-solution of (5.7). By the maximum principle, the conclusion follows.

Step 5. End of proof. Fix $\alpha \in (0, \frac{n-2s}{2})$ given by

$$\alpha = \frac{n-2s}{2} - \frac{2s}{p-1}$$

so that

$$\left(\frac{n-2s}{2} \right)^2 - \alpha^2 = \frac{2s}{p-1} \left(n-2s - \frac{2s}{p-1} \right) = \beta,$$

where β is the constant appearing in (5.3).

Use the stability inequality (5.4) with $\varphi = \frac{\psi \phi_0}{\phi_\alpha}$:

$$(5.9) \quad \kappa_s p \int_{\partial S_+^n} |\psi|^{p+1} \leq \int_{S_+^n} \theta_1^{1-2s} \left| \nabla \left(\frac{\psi \phi_0}{\phi_\alpha} \right) \right|^2 + \left(\frac{n-2s}{2} \right)^2 \int_{S_+^n} \theta_1^{1-2s} \left(\frac{\psi \phi_0}{\phi_\alpha} \right)^2.$$

Note that a particular case of the identity (5.6) is

$$(5.10) \quad \int_{S_+^n} \theta_1^{1-2s} |\nabla \varphi|^2 + \left(\frac{n-2s}{2} \right)^2 \int_{S_+^n} \theta_1^{1-2s} \varphi^2 = \kappa_s \Lambda_{n,s} \int_{\partial S_+^n} \varphi^2 + \int_{S_+^n} \theta_1^{1-2s} \phi_0^2 \left| \nabla \left(\frac{\varphi}{\phi_0} \right) \right|^2$$

Using (5.10) (with $\varphi = \frac{\psi \phi_0}{\phi_\alpha}$), (5.9) becomes

$$\kappa_s p \int_{\partial S_+^n} |\psi|^{p+1} \leq \kappa_s \Lambda_{n,s} \int_{\partial S_+^n} \psi^2 + \int_{S_+^n} \theta_1^{1-2s} \phi_0^2 \left| \nabla \left(\frac{\psi}{\phi_\alpha} \right) \right|^2.$$

By (5.8), we deduce that

$$\kappa_s p \int_{\partial S_+^n} |\psi|^{p+1} \leq \kappa_s \Lambda_{n,s} \int_{\partial S_+^n} \psi^2 + \int_{S_+^n} \theta_1^{1-2s} \phi_\alpha^2 \left| \nabla \left(\frac{\psi}{\phi_\alpha} \right) \right|^2.$$

Using again the identity (5.6), we deduce that

$$\kappa_s p \int_{\partial S_+^n} |\psi|^{p+1} \leq \kappa_s (\Lambda_{n,s} - \lambda(\alpha)) \int_{\partial S_+^n} \psi^2 + \int_{S_+^n} \theta_1^{1-2s} |\nabla \psi|^2 + \beta \int_{S_+^n} \theta_1^{1-2s} \psi^2$$

Comparing with (5.2), it follows that

$$(5.11) \quad (p-1) \int_{\partial S_+^n} |\psi|^{p+1} \leq (\Lambda_{n,s} - \lambda(\alpha)) \int_{\partial S_+^n} \psi^2.$$

But from (5.2) and (5.6)

$$\int_{\partial S_+^n} |\psi|^{p+1} \geq \lambda(\alpha) \int_{\partial S_+^n} \psi^2$$

Combined with (5.11), we find that

$$\lambda(\alpha)p \leq \Lambda_{n,s}$$

unless $\psi \equiv 0$. □

6. BLOW-DOWN ANALYSIS

Proof of Theorem 1.1. Assume that $p > p_S(n)$. Take a solution u of (1.3) which is stable outside the ball of radius R_0 and let \bar{u} be its extension solving (1.10).

Step 1. $\lim_{\lambda \rightarrow +\infty} E(\bar{u}, 0; \lambda) < +\infty$.

Since E is nondecreasing, it suffices to show that $E(\bar{u}, 0; \lambda)$ is bounded. Write $E = E_1 + E_2$, where E_1 is given by (4.1) and

$$E_2(\bar{u}; \lambda) = \lambda^{2s \frac{p+1}{p-1} - n-1} \frac{s}{p+1} \int_{\partial B(0, \lambda) \cap \mathbb{R}_+^{n+1}} t^{1-2s} \bar{u}^2 d\sigma$$

By Lemma 2.6, E_1 is bounded. Since E is nondecreasing,

$$E(\bar{u}; \lambda) \leq \frac{1}{\lambda} \int_{\lambda}^{2\lambda} E(u; t) dt \leq C + \lambda^{2s \frac{p+1}{p-1} - n-1} \int_{B_{2\lambda} \cap \mathbb{R}_+^{n+1}} t^{1-2s} \bar{u}^2.$$

Applying Lemma 2.5, we deduce that E is bounded.

Step 2. There exists a sequence $\lambda_i \rightarrow +\infty$ such that (\bar{u}^{λ_i}) converges weakly in $H_{loc}^1(\mathbb{R}_+^{n+1}; t^{1-2s} dx dt)$ to a function \bar{u}^∞ .

This follows from the fact that (\bar{u}^{λ_i}) is bounded in $H_{loc}^1(\mathbb{R}_+^{n+1}; t^{1-2s} dx dt)$ by Lemma 2.6.

Step 3. \bar{u}^∞ is homogeneous

To see this, apply the scale invariance of E , its finiteness and the monotonicity formula: given $R_2 > R_1 > 0$,

$$\begin{aligned} 0 &= \lim_{n \rightarrow +\infty} E(\bar{u}; \lambda_i R_2) - E(\bar{u}; \lambda_i R_1) \\ &= \lim_{n \rightarrow +\infty} E(\bar{u}^{\lambda_i}; R_2) - E(\bar{u}^{\lambda_i}; R_1) \\ &\geq \liminf_{n \rightarrow +\infty} \int_{(B_{R_2} \setminus B_{R_1}) \cap \mathbb{R}_+^{n+1}} t^{1-2s} r^{2-n+\frac{4s}{p-1}} \left(\frac{2s}{p-1} \frac{\bar{u}^{\lambda_i}}{r} + \frac{\partial \bar{u}^{\lambda_i}}{\partial r} \right)^2 dx dt \\ &\geq \int_{(B_{R_2} \setminus B_{R_1}) \cap \mathbb{R}_+^{n+1}} t^{1-2s} r^{2-n+\frac{4s}{p-1}} \left(\frac{2s}{p-1} \frac{\bar{u}^\infty}{r} + \frac{\partial \bar{u}^\infty}{\partial r} \right)^2 dx dt \end{aligned}$$

Note that in the last inequality we only used the weak convergence of (\bar{u}^{λ_i}) to \bar{u}^∞ in $H_{loc}^1(\mathbb{R}_+^{n+1}; t^{1-2s} dx dt)$. So,

$$\frac{2s}{p-1} \frac{\bar{u}^\infty}{r} + \frac{\partial \bar{u}^\infty}{\partial r} = 0 \quad \text{a.e. in } \mathbb{R}_+^{n+1}.$$

And so, u^∞ is homogeneous.

Step 4. $\bar{u}^\infty \equiv 0$

Simply apply Theorem 5.1.

Step 5. (\bar{u}^{λ_i}) converges strongly to zero in $H^1(B_R \setminus B_\epsilon; t^{1-2s} dx dt)$ and (u^{λ_i}) converges strongly to zero in $L^{p+1}(B_R \setminus B_\epsilon)$ for all $R > \epsilon > 0$. Indeed, by Steps 2 and 3, (\bar{u}^{λ_i}) is bounded in $H_{loc}^1(\mathbb{R}_+^{n+1}; t^{1-2s} dx dt)$ and converges weakly to 0. It follows that (\bar{u}^{λ_i}) converges strongly to 0 in $L_{loc}^2(\mathbb{R}_+^{n+1}; t^{1-2s} dx dt)$. Indeed, by the standard Rellich-Kondrachov theorem and a diagonal argument, passing to a subsequence we obtain

$$\int_{\mathbb{R}_+^{n+1} \cap (B_R \setminus A)} t^{1-2s} |\bar{u}^{\lambda_i}|^2 dx dt \rightarrow 0,$$

as $i \rightarrow \infty$, for any $B_R = B_R(0) \subset \mathbb{R}^{n+1}$ and A of the form $A = \{(x, t) \in \mathbb{R}_+^{n+1} : 0 < t < r/2\}$, where $R, r > 0$. By [15, Theorem 1.2],

$$\int_{\mathbb{R}_+^{n+1} \cap B_r(x)} t^{1-2s} |\bar{u}^{\lambda_i}|^2 dx dt \leq Cr^2 \int_{\mathbb{R}_+^{n+1} \cap B_r(x)} t^{1-2s} |\nabla \bar{u}^{\lambda_i}|^2 dx dt$$

for any $x \in \partial \mathbb{R}_+^{n+1}$, $|x| \leq R$, with a uniform constant C . Covering $B_R \cap A$ with half balls $B_r(x) \cap \mathbb{R}_+^{n+1}$, $x \in \partial \mathbb{R}_+^{n+1}$ with finite overlap, we see that

$$\int_{B_R \cap A} t^{1-2s} |\bar{u}^{\lambda_i}|^2 dx dt \leq Cr^2 \int_{B_R \cap A} t^{1-2s} |\nabla \bar{u}^{\lambda_i}|^2 dx dt \leq Cr^2,$$

and from this we conclude that (\bar{u}^{λ_i}) converges strongly to 0 in $L_{loc}^2(\mathbb{R}_+^{n+1}; t^{1-2s} dx dt)$.

Now, using (2.7), (\bar{u}^{λ_i}) converges strongly to 0 in $H_{loc}^1(\mathbb{R}_+^{n+1} \setminus \{0\}; t^{1-2s} dx dt)$ and by (2.6), the convergence also holds in $L_{loc}^{p+1}(\mathbb{R}^n \setminus \{0\})$.

Step 6. $\bar{u} \equiv 0$.

Indeed,

$$\begin{aligned} E_1(\bar{u}; \lambda) &= E_1(\bar{u}^\lambda; 1) = \int_{\mathbb{R}_+^{n+1} \cap B_1} t^{1-2s} \frac{|\nabla \bar{u}^\lambda|^2}{2} dx dt - \int_{\partial \mathbb{R}_+^{n+1} \cap B_1} \frac{\kappa_s}{p+1} |\bar{u}^\lambda|^{p+1} dx \\ &= \int_{\mathbb{R}_+^{n+1} \cap B_\epsilon} t^{1-2s} \frac{|\nabla \bar{u}^\lambda|^2}{2} dx dt - \int_{\partial \mathbb{R}_+^{n+1} \cap B_\epsilon} \frac{\kappa_s}{p+1} |\bar{u}^\lambda|^{p+1} dx + \\ &\quad \int_{\mathbb{R}_+^{n+1} \cap B_1 \setminus B_\epsilon} t^{1-2s} \frac{|\nabla \bar{u}^\lambda|^2}{2} dx dt - \int_{\partial \mathbb{R}_+^{n+1} \cap B_1 \setminus B_\epsilon} \frac{\kappa_s}{p+1} |\bar{u}^\lambda|^{p+1} dx \\ &= \varepsilon^{n-2s \frac{p+1}{p-1}} E_1(\bar{u}; \lambda \varepsilon) + \int_{\mathbb{R}_+^{n+1} \cap B_1 \setminus B_\epsilon} t^{1-2s} \frac{|\nabla \bar{u}^\lambda|^2}{2} dx dt - \int_{\partial \mathbb{R}_+^{n+1} \cap B_1 \setminus B_\epsilon} \frac{\kappa_s}{p+1} |\bar{u}^\lambda|^{p+1} dx \\ &\leq C \varepsilon^{n-2s \frac{p+1}{p-1}} + \int_{\mathbb{R}_+^{n+1} \cap B_1 \setminus B_\epsilon} t^{1-2s} \frac{|\nabla \bar{u}^\lambda|^2}{2} dx dt - \int_{\partial \mathbb{R}_+^{n+1} \cap B_1 \setminus B_\epsilon} \frac{\kappa_s}{p+1} |\bar{u}^\lambda|^{p+1} dx \end{aligned}$$

Letting $\lambda \rightarrow +\infty$ and then $\varepsilon \rightarrow 0$, we deduce that $\lim_{\lambda \rightarrow +\infty} E_1(\bar{u}; \lambda) = 0$. Using the monotonicity of E ,

$$E(\bar{u}; \lambda) \leq \frac{1}{\lambda} \int_\lambda^{2\lambda} E(t) dt \leq \sup_{[\lambda, 2\lambda]} E_1 + C \lambda^{-n-1+2s \frac{p+1}{p-1}} \int_{B_{2\lambda} \setminus B_\lambda} \bar{u}^2$$

and so $\lim_{\lambda \rightarrow +\infty} E(\bar{u}; \lambda) = 0$. Since u is smooth, we also have $E(\bar{u}; 0) = 0$. Since E is monotone, $E \equiv 0$ and so \bar{u} must be homogeneous, a contradiction unless $\bar{u} \equiv 0$. \square

7. CONSTRUCTION OF RADIAL ENTIRE STABLE SOLUTIONS

Let \bar{u}_s denote the extension of the singular solution u_s (1.7) to \mathbb{R}_+^{n+1} defined by

$$\bar{u}_s(X) = \int_{\mathbb{R}^n} P(X, y) u(y) dy.$$

Let B_1 denote the unit ball in \mathbb{R}^{n+1} and for $\lambda \geq 0$, consider

$$(7.1) \quad \begin{cases} \operatorname{div}(t^{1-2s} \nabla u) = 0 & \text{in } B_1 \cap \mathbb{R}_+^{n+1} \\ u = \lambda \bar{u}_s & \text{on } \partial B_1 \cap \mathbb{R}_+^{n+1} \\ -\lim_{t \rightarrow 0} (t^{1-2s} u_t) = \kappa_s u^p & \text{on } B_1 \cap \{t = 0\}. \end{cases}$$

Take $\lambda \in (0, 1)$. Since u_s is a positive supersolution of (7.1), there exists a minimal solution $u = u_\lambda$. By minimality, the family (u_λ) is nondecreasing and u_λ is axially symmetric, that is, $u_\lambda(x, t) = u_\lambda(r, t)$ with $r = |x| \in [0, 1]$. In addition, for a fixed value $\lambda \in (0, 1)$, u_λ is bounded, as can be proved by the truncation method of [1], see also [10] and radially decreasing by the moving plane method (see [7] for a similar setting). From now on let us assume that $p_S(n) < p$ and

$$p \frac{\Gamma(\frac{n}{2} - \frac{s}{p-1}) \Gamma(s + \frac{s}{p-1})}{\Gamma(\frac{s}{p-1}) \Gamma(\frac{n-2s}{2} - \frac{s}{p-1})} \leq \frac{\Gamma(\frac{n+2s}{4})^2}{\Gamma(\frac{n-2s}{4})^2},$$

which means that the singular solution u_s is stable. Then, $u_\lambda \uparrow u_s$ as $\lambda \uparrow 1$, using the classical convexity argument in [2] (see also Section 3.2.2 in [14]). Let $\lambda_j \uparrow 1$ and

$$m_j = \|u_{\lambda_j}\|_{L^\infty} = u_{\lambda_j}(0), \quad R_j = m_j^{\frac{p-1}{2s}},$$

so that $m_j, R_j \rightarrow \infty$ as $j \rightarrow \infty$. Set

$$v_j(x) = m_j^{-1} u_{\lambda_j}(x/R_j).$$

Then $0 \leq v_j \leq 1$ is a bounded solution of

$$\begin{cases} \operatorname{div}(t^{1-2s} \nabla v_j) = 0 & \text{in } B_{R_j} \cap \mathbb{R}_+^{n+1} \\ v_j = \lambda_j \bar{u}_s & \text{on } \partial B_{R_j} \cap \mathbb{R}_+^{n+1} \\ -\lim_{t \rightarrow 0} (t^{1-2s} (v_j)_t) = \kappa_s v_j^p & \text{on } B_{R_j} \cap \{t = 0\}. \end{cases}$$

Moreover $v_j \leq \bar{u}_s$ in $B_{R_j} \cap \mathbb{R}_+^{n+1}$ and $v_j(0) = 1$. Using elliptic estimates we find (for a subsequence) that (v_j) converges uniformly on compact sets of $\bar{\mathbb{R}}_+^{n+1}$ to a function v that is axially symmetric and solves

$$\begin{cases} \operatorname{div}(t^{1-2s} \nabla v) = 0 & \text{in } \mathbb{R}_+^{n+1} \\ -\lim_{t \rightarrow 0} (t^{1-2s} v_t) = \kappa_s v^p & \text{on } \mathbb{R}^n \times \{0\}. \end{cases}$$

Moreover $0 \leq v \leq 1$, $v(0) = 1$ and $v \leq \bar{u}_s$. This v restricted to $\mathbb{R}^n \times \{0\}$ is a radial, bounded, smooth solution of (1.3) and from $v \leq \bar{u}_s$ we deduce that v is stable.

Acknowledgments: J. Dávila is supported by Fondecyt 1130360 and Fondo Basal CMM, Chile. The research of J. Wei is partially supported by NSERC of Canada. L. Dupaigne is partially supported by ERC grant Epsilon.

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DEPARTAMENTO DE INGENIERÍA MATEMÁTICA AND CMM, UNIVERSIDAD DE CHILE, CASILLA 170 CORREO 3, SANTIAGO, CHILE
E-mail address: `jdavila@dim.uchile.cl`

INSTITUT CAMILLE JORDAN, UMR CNRS 5208, UNIVERSITÉ CLAUDE BERNARD LYON 1, 43 BOULEVARD DU 11 NOVEMBRE 1918, 69622 VILLEURBANNE CEDEX, FRANCE
E-mail address: `louis.dupaigne@math.cnrs.fr`

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, B.C., CANADA, V6T 1Z2.
E-mail address: `jcwei@math.ubc.ca`